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MEASUREMENT OF $B^0\overline{B}^0$ MIXING AT CDF

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ABSTRACT

Using dileptons ($e\mu$, ee) to tag B hadron decays, the average $B^0\overline{B}^0$ mixing parameter χ is measured in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. From the $e\mu$ channel, we obtain $\chi = 0.179 \pm 0.027$ (stat) $\pm$ 0.022 (sys) $\pm$ 0.032 (model), and from the ee channel, $\chi = 0.172 \pm 0.060$ (stat) $\pm$ 0.024 (sys) $\pm$ 0.026 (model), where the last uncertainty is due to Monte Carlo modeling.

1. Introduction

Weak interaction does not conserve quark flavor. Heavy quark decaying into lighter quarks gives a common example (e. g. $b \to c$) of quark flavor mixing. This is well represented by the Cabbibo-Kobayashi-Maskawa (CKM) matrix. Transformation of neutral mesons into their antiparticles provides unique demonstrations of quark-antiquark transition. Such phenomenon was first observed in the $K^0\overline{K}^0$ system. The long lifetime of the K^0 meson allows this transition to be observed. The $B^0\overline{B}^0$ is the only other system where sizable mixing behavior is expected. The mixing of $B^0\overline{B}^0$ was observed earlier at the CERN $p\bar{p}$ collider[1] and at e^+e^- colliders.[2,3] Recently, there are new measurements of the average mixing parameter χ above the B_s threshold.[4-6] Here we report the measurement of $B^0\overline{B}^0$ mixing obtained by the CDF collaboration at the Fermilab Tevatron.[7]

1.1. *B Tagging Using Leptons*

In the measurement of $B^0\overline{B}^0$ mixing, one needs to tag the B hadron flavor. This is most simply achieved using the semiletonic decay channels. The following quark level decays illustrate such tagging, $b \to \ell^- \, c \, \bar{\nu}_\ell$ or $\bar{b} \to \ell^+ \, \bar{c} \, \nu_\ell$. Without *mixing* and *sequential* decays, only opposite-sign (OS) dileptons are produced as $b\bar{b} \longrightarrow \ell^+\ell^-$. If one of the b's in the initial state changes its flavor via mixing $b \to \overline{B}^0(b\bar{d}) \to B^0(\bar{b}d) \to \ell^+$, like-sign (LS) dileptons will be produced. Therefore, LS dileptons are the signal for mixing. However, LS pairs can also appear without mixing. Sequential decays can lead to LS dileptons and complicate the mixing measurement, e. g. $b \to c \to \ell^+$.

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Due to the kinematic cuts (P_T cut for example), the sequential events are significantly suppressed relative to the direct semileptonic decays. After subtracting the background, one expects a large charge asymmetry in the dilepton events if no mixing exists.

1.2. *Measurement Method*

With lepton tagging the B hadron flavor, the probability of $B^0\overline{B}^0$ mixing can be expressed as

$$\chi = \frac{prob(b \rightarrow \overline{B}^0 \rightarrow B^0 \rightarrow \ell^+)}{prob(b \rightarrow \ell^\pm)} \quad ,$$

where the leptons can come from both direct and sequential B decays and the denominator includes all possible hadrons formed with the b quark. This parameter is clearly an average over neutral B mesons (B^0_d and B^0_s), which can mix with their antiparticles, and all other B hadrons produced, which do not mix.

For mixing measurement, we first determine a charge ratio R from the data. This is defined as

$$R = \frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell^+\ell^-)},$$

where ℓ is the tagging lepton (e or μ). This quantity is related to the mixing parameter χ in the following formula,

$$R = \frac{2\chi(1-\chi) + [(1-\chi)^2 + \chi^2]f_s}{[(1-\chi)^2 + \chi^2] + 2\chi(1-\chi)f_s + f_c}$$

where

$$f_s = \frac{N_s}{N_f} \quad \text{and} \quad f_c = \frac{N_c}{N_f}$$

and

1.) N_f: number of opposite-sign dileptons from $b \rightarrow \ell^- \oplus \bar{b} \rightarrow \ell^+$,

2.) N_s: number of like-sign dileptons from $b \rightarrow c \rightarrow \ell^+ \oplus \bar{b} \rightarrow \ell^+$, or *c.c.*

3.) N_c: number of opposite-sign dileptons from $c\bar{c}$ decay $c \rightarrow \ell^+ \oplus \bar{c} \rightarrow \ell^-$

Without mixing, above formula can be reduced to $R_0 = \dfrac{N_s}{N_f + N_c} = \dfrac{f_s}{1+f_c}$. Mixing enhances R (*i. e.* $R \geq R_0$). A Monte Carlo is used to model the processes 1-3 and determine the two ratios f_s and f_c. Then the mixing parameter χ is extracted from the measured value of R.

2. Relevant Detectors and Triggers

The CDF detector has been described in detail.[8,9] Here we briefly describe features most relevant to this analysis. A vertex time projection chamber (VTPC) was used for track vertex measurement in the beam direction. A large central tracking chamber (CTC) measures momenta for charged particles in $|\eta| \leq 1.2$ with momentum resolution $\Delta P_T/P_T^2 \simeq 0.0017(\text{ GeV}/c)^{-1}$.[10] Outside the tracking chambers, electromagnetic (EM) and hadronic (Had) calorimeters measure particle energy deposition. In the region $|\eta| \leq 1.1$, wire chambers with cathode strips (CES) are embedded at a depth of six radiation lengths in the EM calorimeters. The CES measures the lateral shape and position of EM showers. Drift chambers for muon detection outside the hadron calorimeter are instrumented in the region $|\eta| \leq 0.63$.

An electron-muon trigger, which was implemented for part of the run, was used to collect most of the $e\mu$ events. A di-electron trigger was used to collect the ee events. In the trigger, the electron candidate was required to have a calorimeter cluster with EM transverse energy $E_T(e) > 5$ GeV, a ratio of hadronic to EM energy of less than 0.125, and an associated track of transverse momentum $P_T(e) > 3$ GeV/c. The muon candidate was required to have a track with transverse momentum $P_T(\mu) > 3$ GeV/c and a matching track segment in the muon chambers. The integrated luminosity for the $e\mu$ and ee trigger are 2.7 pb^{-1} and 3.7 pb^{-1} respectively.

3. Event Selection

In offline analysis, tight selection criteria are applied for both $e\mu$ and ee events as listed in Table 1, which are described in detail in the reference.[11] Cuts were applied to calorimeter shower profile (Lshare),[12] track quality (the number of CTC hits, track z vertex and distance of closest approach (DCA) were required to be consistent with the primary vertex) and track-muon chamber matching. Electron candidates are required to be in the EM calorimeter fiducial region. Conversion electrons are removed. For best charge measurement, we require one and only one 3D track be associated with the electron candidate. With these selection criteria, 429 like-sign and 911 opposite-sign $e\mu$ candidate events are found in the data.

Since charmed mesons do not have sizable mixing behavior, the decays of a single B hadron via the chain $\mathrm{b} \to \mathrm{c}\ell\nu$ followed by $\mathrm{c} \to \mathrm{s}\ell\nu$ always result in opposite-sign di-leptons. The two leptons in such events typically have a small opening angle and small dilepton invariant mass.[11] To reject these single B events, we require the dilepton invariant mass to be greater than 5 GeV/c^2. After this cut, there are 346 like-sign and 554 opposite-sign $e\mu$ events, composed of 181 $e^+\mu^+$, 165 $e^-\mu^-$, 290 $e^-\mu^+$, and 264 $e^+\mu^-$. In addition, the decays $J/\psi \to e^+e^-$ and $\Upsilon \to e^+e^-$ form a background that would affect the measurement of mixing in the ee channel. The invariant mass cut below 5.0 GeV/c^2 removes the former, and excluding the region $8.0 < M_{ee} < 10.8$ GeV/c^2 removes the latter. After these cuts there are 78 like-sign and 134 opposite-sign ee

Table 1: Electron-muon Event Selection Criteria

e	μ
$E_T \geq 5$ GeV	$P_T \geq 3$ GeV/c
Had/EM ≤ 0.04	EM tower ≤ 2.0 GeV
$E/P \leq 1.4$	Had tower ≤ 4.0 GeV
$\Delta(R\phi) \leq 1.5$ cm	CTC/CMU x match ≤ 10.0 cm
$\Delta(z) \leq 2.5$ cm	CTC/CMU fitting $\chi^2_\mu \leq 10.0$
CES $\chi^2_e \leq 10.0$	CTC hits ≥ 50
	CTC track DCA ≤ 0.5 cm
	$\lvert Z_{trk} - Z_{vtx} \rvert \leq 5.0$ cm

events.

4. Background Subtraction

The background in $e\mu$ and ee samples is different. For $e\mu$ events, since we model $c\bar{c}$ decay using Monte Carlo, the background is only due to fake leptons. For ee events, additional background from Drell-Yan production has to be determined. In the following, we briefly give a description of the background determination method[7,11] for the $e\mu$ events.

Since fake background is directly related to the number of tracks, the lepton candidates per track rate can be used for background estimation. For the $e\mu$ background determination, we first measure a muon per track rate in our minimum-bias events. The muons from minimum-bias sample include all possible sources: real muons from heavy quark semileptonic decays, hadron fake muons, kaon or pion decays, etc. Therefore,

$$f_\mu = \frac{N_\mu}{T_{MBS}} = \frac{N^F_\mu + N^R_\mu}{T_{MBS}} = f^F_\mu + f^R_\mu$$

where N_μ is the number of muons in the minimum-bias sample, consisting of N^R_μ real muons and N^F_μ fake muons, and T_{MBS} is the number of good tracks in the same sample. Thus, f^F_μ is fake muon per track and f^R_μ is real muon per track in an unbiased sample. For the 1988-1989 CDF data, we expect f_μ to be dominated by the fake muon rate.

The number of tracks T_e in an inclusive electron sample is the total number of tracks that can lead to fake $e\mu$ events. T_e also has two parts, one from real electron sub-sample (T^R_e) and the other from the fake electron sub-sample (T^F_e), i. e. $T_e = T^R_e + T^F_e$. Multiplying T_e by f_μ, we get

$$T_e \bullet f_\mu = (T^R_e + T^F_e)(f^F_\mu + f^R_\mu) = T^R_e f^F_\mu + T^F_e f^F_\mu + T^F_e f^R_\mu + T^R_e f^R_\mu$$

On the right side of the equation, the first term is the number of real e fake μ events expected, the second term gives fake e fake μ and the third term is the fake e real μ

Table 2: Monte Carlo Predictions for Ratios f_s and f_c ($e\mu$ events)

ratio	lowest order	gluon splitting	overall
f_s	25.8%	22.4%	24.8%
f_c	5.4%	9.5%	6.6%

events expected. The real muon per track rate from minimum bias events is used here because events triggered by a fake electron do not enhance real muon production from heavy flavor decays. The last term is an over-estimate, which is small due to the large background fraction in low P_T single muons.

Thus, the number of good tracks in an inclusive electron sample multiplied by the inclusive muon per track rate gives the total number of $e\mu$ background events from all categories with some over-estimate. The ratio of this number of background events to the total number of $e\mu$ events observed in the *same* inclusive electron sample gives the fraction of background for the $e\mu$ data. Using this method, we determine that the background fraction in our $e\mu$ sample is $19 \pm 9\%$. The large uncertainty represents the limited statistics for the minimum-bias muon events and possible difference in f_μ due to K/π ratio and track P_T variations.

To subtract background for R measurement, one needs to know the charge correlation, *i. e.* LS:OS, in the background events. This is found[7,11] to be close to 1 for both $e\mu$ and ee samples, except for Drell-Yan contribution. After subtracting the background events, there remain 260 like-sign and 468 opposite-sign $e\mu$ and 55 like-sign and 96 opposite-sign ee events. From these we obtain

$$R(e\mu) = 0.556 \pm 0.048\ (\text{stat})\ ^{+0.035}_{-0.042}\ (\text{sys}),$$

and

$$R(ee) = 0.573 \pm 0.116\ (\text{stat})\ \pm 0.047\ (\text{sys}).$$

5. Monte Carlo Modeling

To extract the mixing parameter χ from R, we need two ratios f_s and f_c as described in *section 1.1.* We use ISAJET Monte Carlo program package[13] to model the no mixing processes. The results are summarized in Table 2. We checked that various relevant quantities are well reproduced by the Monte Carlo, including the high order fraction in our $e\mu$ data. Thus, we obtain $f_s = 0.248 \pm 0.055$, $f_c = 0.066 \pm 0.066$ for $e\mu$ events and $f_s = 0.25 \pm 0.06$, $f_c = 0.02 \pm 0.02$ for ee events. The ratio f_s does not depend on the $b\bar{b}$ production cross-section while f_c is directly proportional to the relative production rates of $c\bar{c}$ and $b\bar{b}$. The difference on f_c for $e\mu$ and ee samples is therefore mainly due to the different P_T cut. The uncertainty on f_s is mainly due to: b and c semileptonic decay branching ratios (15%),[14] b quark fragmentation (10%), higher order processes (10%), etc. We assign a 100% error to the ratio of $c\bar{c}$ and $b\bar{b}$ production cross-sections from ISAJET, which gives a 100% error on the fraction f_c.

6. Results

In the absence of mixing ($\chi = 0.0$), the expected charge ratios would be $R(e\mu) = 0.23 \pm 0.06$ and $R(ee) = 0.24 \pm 0.07$, both of which are inconsistent with the observed values. From the observed values of R for the $e\mu$ and ee events, we obtain $\chi(e\mu)$=0.179 $\pm$ 0.027 (stat) $\pm$ 0.022 (sys) $\pm$ 0.032 (model), $\chi(ee)$=0.172 $\pm$ 0.060 (stat) $\pm$ 0.024 (sys) $\pm$ 0.026 (model). The ee channel is limited by statistics. However, the large uncertainty due to Monte Carlo modeling is evident. Improvements in other B physics measurements such as branching ratios in the near future will significantly reduce such uncertainties. A comparison between the $e\mu$ data and Monte Carlo with the determined mixing shows very good agreement.[7] The two results can be combined which gives

$$\chi=0.176 \pm 0.031 \text{ (stat+sys)} \pm 0.032 \text{ (model)},$$

where the uncorrelated statistical and systematic uncertainties have been combined, and the Monte Carlo model uncertainty treated as common.

This result is consistent with other recent measurements from CERN: L3: $\chi = 0.178^{+0.049}_{-0.040}$,[4] ALEPH: $\chi = 0.132 \pm 0.022$,[5] UA1: $\chi = 0.145 \pm 0.035(stat) \pm 0.014(sys)$.[6] Since the B hadron mixture fraction ($B_d : B_u : B_s : \Lambda_b$) is not measured at any experiments, differences in such fractions may affect direct comparisons.

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